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UNIT PRICE AS A USEFUL METRIC IN ANALYZING EFFECTS OF REINFORCER MAGNITUDE

R. J. DEGRANDPRE, WARREN K. BICKEL, JOHN R. HUGHES, MICHAEL P. LAYNG, AND GARY BADGER

UNIVERSITY OF VERMONT

In this paper, we applied the behavioral-economic concept of unit price to the study of reinforcer magnitude in an attempt to provide a consistent account of the effects of reinforcer magnitude on behavior. Recent research in the experimental analysis of behavior and in behavioral pharmacology suggests that reinforcer magnitude interacts with the schedule of reinforcement to determine response rate and total consumption. The utility of the unit-price concept thus stems from its ability to quantify this interaction as a cost-benefit ratio (i.e., unit price = characteristics of the schedule of reinforcement divided by magnitude of reinforcement). Research employing the unit-price concept has shown that as unit price increases, a positively decelerating function exists for consumption (i.e., a function with an increasingly negative slope, when plotted on log coordinates) and a bitonic function exists for response rate. Based on these findings, the present analysis applied the unit-price concept to those studies of reinforcer magnitude and drug self-administration that examined the effects of reinforcer magnitude on response rate using simple schedules of reinforcement (e.g., fixed-ratio schedule). This resulted in three findings: (a) Reinforcer-magnitude manipulations and schedule manipulations interact in a manner that can be quantified in terms of unit price as benefit and cost factors, respectively; (b) different reinforcer-magnitude manipulations are functionally interchangeable as benefit factors in the unit-price ratio; and (c) these conclusions appear warranted despite differences in reinforcers (food or drug), species (dogs, monkeys, or rats), and schedules (interval or ratio), and despite the fact that these studies were not designed for a unit-price analysis. In methodological terms, these results provide further evidence that employing the unit-price concept is a parsimonious method for examining the effects of reinforcer magnitude. In theoretical terms, these results suggest that a single process may underlie the effect of combined reinforcer-magnitude and schedule manipulations.

Key words: barbiturates, behavioral economics, behavioral pharmacology, behavioral regulation, drug self-administration, law of effect, opioids, reinforcer magnitude, reinforcement schedule, stimulants, unit price

The effects of different reinforcer-magnitude manipulations (i.e., volume, concentration, and duration) are reported as highly varied and often contradictory, both within and across studies. Iglauer and Woods (1974), for example, noted that "in experiments employing single-schedule procedures and nutritive reinforcers . . . consistent magnitude-rate relationships have not been found," noting that increases in absolute reinforcer magnitude have been found to "increase," "change slightly," or "decrease" rate of responding (p. 180). In another example, Bonem and Crossman (1988) reviewed the literature on reinforcer magnitude and noted that "changes in the magnitude of reinforcement do not always produce changes in response, particularly on single schedules of reinforcement" and that some authors have concluded that magnitude effects on response rate are "the exception more than the rule" (p. 348). In yet another example, Collier, Johnson, and Morgan (1992) stated that "the function relating reinforcer magnitude to response rate has been shown to be increasing, decreasing, bitonic, or flat" (p. 81).

The purpose of this paper is to apply the behavioral-economic concept of *unit price* to the study of reinforcer magnitude in an attempt to characterize the effects of reinforcer magnitude better. Unit price quantifies the interaction between response-requirement and reinforcer-magnitude manipulations in terms of a cost-benefit ratio (i.e., schedule of reinforcement divided by magnitude of reinforcement), thus allowing multiple independent variables (e.g., two different magnitude manipulations or reinforcement schedule and reinforcer magnitude) to be subsumed into a sin-

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gle variable (unit price) (Bickel, DeGrandpre, Higgins, & Hughes, 1990; DeGrandpre & Bickel, in press; Hursh, Raslear, Shurtleff, Bauman, & Simmons, 1988). Different types of reinforcer-magnitude manipulations therefore may have the same functional effect via their role in determining unit price. For example, if behavior is sensitive to unit price, doubling the volume of the reinforcer (or doubling the concentration of the reinforcer) should have the same functional effects on behavior by decreasing unit price by one half, and either of these manipulations should be equivalent to halving the response requirement.

Recent applications of unit price to the experimental analysis of behavior and behavioral pharmacology have shown that reinforcer magnitude interacts with the schedule of reinforcement to determine response rate and total consumption (e.g., Bickel et al., 1990; DeGrandpre & Bickel, in press; Hursh et al., 1988). A second finding from the application of unit price is that, as unit price increases, a positively decelerating function exists for consumption and a bitonic function exists for response rate (on log coordinates; DeGrandpre & Bickel, in press; Hursh et al., 1988).

The effects of unit price on consumption are typically described in economic terms as *demand.* The demand curve is used to describe the amount of a commodity consumed as a function of the price of that commodity, and is typically shown on log coordinates to represent proportional change (Samuelson & Nordhaus, 1985). Because demand simply refers to consumption of the reinforcer at a given unit price, "consumption" will be used instead of "demand" in what follows to avoid confusion. *Elasticity* is another economic term related to consumption and refers to the degree to which consumption changes (proportionally) as unit price changes (in log space, elasticity = slope) (Hursh & Bauman, 1987). Reinforcers for which consumption changes greatly with increased price are said to be elastic (e.g., luxuries); those that change little with increased price are said to be inelastic (e.g., necessities). Note, however, that commodities can have a mixed elasticity, such that elasticity increases as unit price increases (Hursh & Bauman, 1987).

Although the effects of unit price on consumption are discussed in this paper, the primary focus is on the effects of unit price on response rate. Indicators of the behavioral effects of reinforcer magnitude have primarily included response rate, although measures such as postreinforcement pause (PRP), running speed (e.g., feet per second), number of reinforcers delivered (e.g., number of self-administrations), and amount of reinforcer consumed have also been offered. In addition to being a common dependent variable in reinforcer-magnitude studies, response rate is also a common measure of response strength (Collier et al., 1992; see Williams, 1988, for a detailed discussion of response strength). In the experimental analysis of behavior, response rate has been cited as one indicator of the strength of an operant (Skinner, 1938; Williams, 1988). In behavioral pharmacology, response rate is commonly used as an assessment of reinforcer "value" or "efficacy" (e.g., see Katz, 1990).

The two findings in unit-price analyses—the interaction of cost and benefit factors and the positively decelerating function—may permit an alternative and unifying interpretation of the seemingly inconsistent effects of reinforcer magnitude on response rate and consumption. In applying the unit-price concept to reinforcer magnitude in this paper, we shall attempt to (a) review recent unit-price studies to demonstrate their relevance to issues of reinforcer magnitude, (b) quantify data from reinforcer-magnitude studies (for both food and drug reinforcers) in unit-price terms, and (c) discuss possible methodological and theoretical benefits and limitations of a unit-price analysis versus existing interpretations. In attempting to fulfill these three objectives, this paper does not provide a review of the literature on reinforcer magnitude (for a recent review, see Bonem & Crossman, 1988). Rather, the scope of the paper limits its focus to the effects of reinforcer magnitude on response rates associated with drug- and food-maintained behavior of nonhuman animals when reinforcement is delivered according to a simple schedule of reinforcement. To avoid a bias in the selection of articles reviewed, we established explicit criteria for their selection (discussed below). Finally, data on choice behavior under concurrent schedules are not included because they are likely to require a separate analysis (see Bickel, DeGrandpre, & Higgins, in press).

Recent Unit-Price Analyses

One of the first prospective tests of the notion of functional equivalence between reinforcement-schedule and reinforcer-magnitude manipulations examined food-maintained behavior in rats in a closed economy (i.e., all food consumed was earned during the experimental session; Hursh et al., 1988). This study varied the cost factors (response requirement and response force) and the benefit factors (probability of reinforcer delivery and reinforcer volume). Response rate (and consumption) was equal at equal unit prices regardless of the various constituents making up the unit price, demonstrating the utility of the unit-price concept. Hursh et al. also reported that elasticity increased as unit price increased. In other words, as unit price increased, consumption of the reinforcer initially decreased little until some unit price at which it rapidly decreased (this is referred to below as a positively decelerating consumption function). In terms of response rate, this study showed that as unit price increased, response rate increased until some unit price at which response rate reached a maximum and then fell rapidly (see Figure 1; see Figure 3 in Hursh et al. showing consumption as a function of unit price). This relationship between consumption (a positively decelerating function) and response rate (a bitonic function) is mathematically predictable when employing ratio schedules because of the deterministic relationship between these two dependent variables.

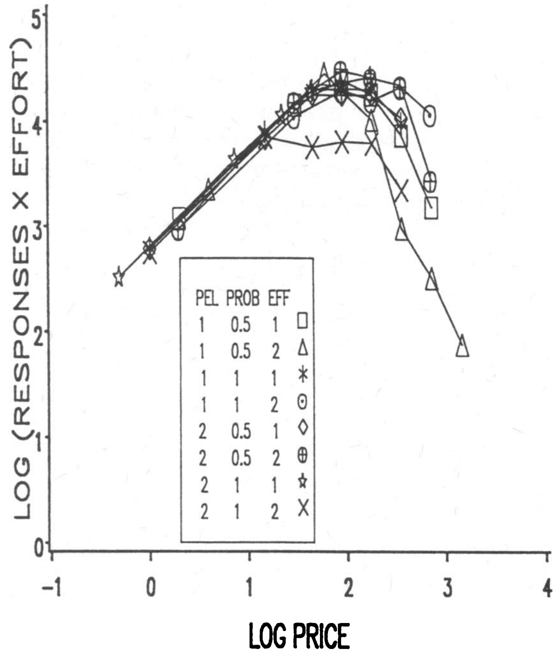


Fig. 1. For each condition, the log median responses per day times effort are shown as a function of unit price (in log units). This figure is from Hursh et al. (1988, Figure 5), and is reprinted with permission. Different symbols represent different combinations of volume (number of pellets), probability of reinforcement, and response effort.

Following the study of food-maintained behavior in rats by Hursh et al. (1988), the unit-price concept was applied to the laboratory study of drug taking (i.e., drug self-administration). First, a reanalysis of nonhuman drug self-administration studies that manipulated both fixed-ratio (FR) response requirement and drug dose was conducted. For example, one study examined oral consumption of a pentobarbital-ethanol combination in rhesus monkeys (Lemaire & Meisch, 1985). Different combinations of FR values (8, 16, 32, 64, 128, 256, 512, and 1,024) and the number of oral pentobarbital-ethanol presentations received after completing the FR (1, 2, 4, 8, 16, 32, 64, 128, and 256), when reanalyzed, produced several replications of five unit prices (64, 32, 16, 8, and 4 responses per mg/mL pentobarbital with 1% ethanol) with different cost and benefit factors (e.g., both FR 8 ÷ 2 drug deliveries and FR 64 ÷ 16 drug deliveries produced a unit price of four responses per mg/mL pentobarbital with 1% ethanol). This and the other reanalyzed studies generally showed that drug consumption was equal at equal unit prices, and consumption was a positively decelerating function of unit price (Bickel et al., 1990).

These two findings have been replicated in two prospective studies; one examined the effects of unit price on drug consumption in 5 human cigarette smokers by manipulating FR response requirement and number of puffs per FR (Bickel, DeGrandpre, Hughes, & Higgins, 1991), and the other examined the unit-price concept in rhesus monkeys responding for phencyclidine (PCP; Carroll, Carmona, & May, 1991). Also, the effects of unit price were examined in a recent reanalysis of 17 studies testing the nicotine-regulation hypothesis (DeGrandpre, Bickel, Hughes, & Higgins, 1992). This analysis showed that manipulating the nicotine in smokers' cigarettes (e.g., via brand switching) was equivalent to changes in unit price (unit price was the inverse of nicotine yield), in that nicotine consumption decreased as unit price increased in a positively decelerating fashion.

Each of the unit-price analyses described above examined the effects of reinforcer magnitude. All four of the studies in which both reinforcement schedule and reinforcer magnitude were manipulated confirmed that schedule and magnitude interact in a quantifiable manner to determine consumption, at least with FR schedules of reinforcement. Also, all five studies suggest a positively decelerating curve for consumption and a bitonic function for response rate, regardless of reinforcer (e.g., food or drug), species (e.g., human or animal), or magnitude manipulation (e.g., volume or concentration). Based on the generality and implications of these findings, we chose to conduct the following analysis.

USING UNIT PRICE TO ANALYZE EFFECTS OF REINFORCER MAGNITUDE

Methods

Reinforcer-magnitude studies were located via *Medline* and *Psychological Abstracts* literature searches for the years 1966 through 1992 using the following key words: *reinforcer magnitude, reinforcer concentration, reinforcer duration,* and *reinforcer volume,* or *drug self-administration, drug reinforcement,* and *reinforcement schedule.* Additional studies were also located in the references of reinforcer-magnitude or drug self-administration studies or reviews already identified. Data were derived from tables when available and were estimated from graphs when tables were not available. When estimations were made from graphed data, the graphs were enlarged (via photocopier) and a grid overlay was used to increase precision.

Data from studies that manipulated one or more reinforcer-magnitude factors (i.e., concentration, duration, or volume of the reinforcer) were reanalyzed. Although, in terms of unit price, schedule of reinforcement is directly related to reinforcer magnitude, we do not present data from studies that manipulated only the schedule of reinforcement. In this paper, unit price will equal the product of the cost factors divided by the product of the benefit factors. The cost factor for interval schedules will be the interval duration, and the cost factor for ratio schedules will be the response requirement (discussed in greater detail below). In presenting these data, we attempted either to (a) compare data across studies with the same schedule (interval or ratio), species, and reinforcer, or (b) provide detailed reviews of studies that, in unit-price terms, shed light on the reinforcer-magnitude issue. As an example of the former, six experiments in four studies were located that used rats as subjects, a sucrose reinforcer, interval schedules, and a reinforcer volume and/or concentration manipulation of reinforcer magnitude. Hence, a unit-price ratio was used that included the schedule interval (seconds) as the cost factor and the product of the concentration (percentage) and volume (milliliter) values as the benefit factor (even if one of these terms was not varied). Using this ratio, the response rates of one species (rats) could be plotted as a function of one variable (unit price) that integrates all the factors manipulated across all six experiments. Comparisons of multiple independent variables are thus facilitated by the unit-price ratio by reducing all the manipulations to the same unit-price dimensions (e.g., responses per milligram with ratio schedules; minimum seconds per milligram with interval schedules). Also, consumption data from magnitude studies that reported both response rate and consumption are provided in order to examine the relationship between these two dependent measures across different reinforcer-magnitude and schedule manipulations.

Many studies originally presented group data. Thus, when single-subject data were reported, the response-rate data from all subjects were grouped as a mean for each experimental condition. This also allowed us to avoid the problem of presenting data from all subjects in these studies (which would require a great amount of space) and to avoid choosing data from "representative" subjects. Although this group method eliminates individual differences, the results are nonetheless representative of the individual-subject data in most cases. One exception to this procedure was made, because data from only 1 subject were reported in one of the experiments (Peden & Timberlake, 1984). In some drug self-administration studies, a single subject responded for the drug at a particular dose that differed from other subjects; in this case, we excluded data points from manipulations that occurred for only 1 subject. Also, studies are presented here only if they assessed at least four unit prices (i.e., four conditions; one exception exists that is used for illustration purposes). This criterion was used because three or fewer data points are typically ambiguous to interpret in terms of a nonlinear model. Data from studies that manipulated reinforcer magnitude within a session or placed a ceiling on total consumption also were not reanalyzed.

To limit the large number of drug self-administration studies to be reanalyzed, we imposed two additional criteria. First, we chose only those studies that examined drugs from the barbiturate, opioid, and stimulant drug classes. These drug classes represent the most commonly studied drugs in drug self-administration research. Second, we reanalyzed a study (or an experiment within a study) only if there was at least one additional study that examined (a) the same drug (b) via the same route of administration (c) with the same reinforcement schedule and (d) in the same species. This second criterion was chosen because it limits the number of studies while promoting comparisons across studies. Note that drug self-administration studies employ closed economies, in that the self-administered drug is not available outside the experimental session. Also note that none of the above criteria were used to eliminate studies that reported data inconsistent with previous research on unit price. Finally, data from three drug self-administration studies reanalyzed in Bickel et al. (1990), which manipulated both FR response requirement and drug dose, are presented below because they meet the above selection criteria.

Data from studies of food-maintained responding will be reviewed first, followed by data from studies of drug-maintained responding. Table 1 outlines each study (for both food and drug reinforcement). Some studies are represented twice because more than one drug was examined.

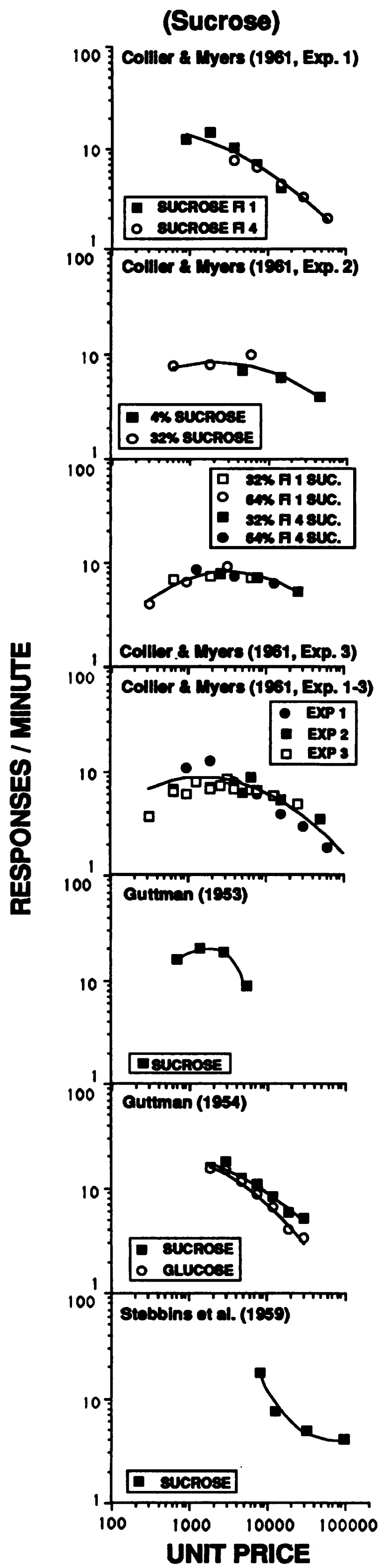
Reinforcer Magnitude and Food-Maintained Responding

In this section, data are examined from 10 studies (16 experiments) in which sucrose or dry food (i.e., a portion of the daily food ration) maintained responding. Studies using a sucrose solution as the reinforcer will be discussed first. The functional equivalence of different reinforcer-magnitude and schedule manipulations, if applicable, will be described for each study first, followed by the shape of the function for consumption and then response rate.

Sucrose. Four studies examined the effects of sucrose in rats using interval schedules (Collier & Myers, 1961; Guttman, 1953, 1954; Stebbins, Mead, & Martin, 1959). Each of these studies employed a closed economy, in that sucrose was not available outside the experimental session; however, because sucrose has some caloric value and because food was available outside the session, these procedures could also be considered to be an open economy (cf. Smith & Foster, 1980). We denote this mixed open/closed economy in Table 1 as "open?"

The most comprehensive of these four studies (Collier & Myers, 1961) examined sucrose-maintained responding in rats across three experiments in which a fixed-interval (FI) schedule (Experiments 1 and 3), reinforcer concentration (Experiments 1–3), and reinforcer volume (Experiments 2 and 3) were varied. Experiment 1, when reanalyzed in terms of unit price, has three unit prices that are replicated with different cost-benefit values by varying the reinforcement schedule (FI 1 min and FI 4 min) and the concentration of the sucrose solution (4, 8, 16, 32, and 64%); replicated unit-price ratios were 1,500 s/mg, where time (seconds) is the minimum delay per milligram of reinforcer imposed by the interval schedule (60 s ÷ 0.04 mg and 240 s ÷ 0.16 mg), 750 s/mg (60 s ÷ 0.8 mg and 240 s ÷ 0.32 mg), and 375 s/mg (60 s ÷ 0.16 mg and 240 s ÷ 0.64 mg).

As shown in Figure 2, the different schedule and magnitude manipulations interact to produce what could be described as a single bitonic function for response rate (see top three graphs; the fourth graph from the top shows the composite for all three experiments; a quadratic equation was used as a simple method for fitting a line of best fit to the response-rate data on log coordinates). This appears to be the case despite the fact that one reinforcement-schedule manipulation and two reinforcer-magnitude manipulations were made across the three studies. This finding is not apparent when the data are plotted using a more traditional method, as shown in Figure 3 (see Collier & Myers, 1961). Figure 3 shows response rate plotted on the y axis as a function of one reinforcer-magnitude manipulation (volume) on the x axis. This graph appears to demonstrate a somewhat peculiar finding: At the 32% concentration on the FI 4-min schedule, increases in volume generally *increased* the rate of responding across the two schedules' parameters,



whereas at the 64% concentration on the FI 1-min schedule, increases in volume *decreased* rate of responding. This presentation of these data suggests that reinforcer magnitude and schedule interact in a manner that could not be predicted a priori, a conclusion that is not supported when the data are plotted as a function of unit price.

The data from the three additional studies that examined sucrose-maintained responding in rats are plotted as a function of unit price—interval (not manipulated) ÷ [concentration (manipulated) × volume (unmanipulated)]—and are shown in the bottom three graphs of Figure 2. Note that glucose-maintained responding is also shown for Guttman (1954). The effects of reinforcer magnitude on response rate in these studies, when plotted in unit-price terms, are generally consistent with the data from Collier and Myers (1961). That is, those data from Guttman (1953) that show a positive relationship between response rate and unit price occur within a range of unit prices that is consistent with the data from Collier and Myers (1961), as is the range of unit prices in these latter three studies in which an inverse relationship exists between response rate and unit price. Overall, the data from all four studies illustrated in Figure 2 show that the unit-price analysis produces a single variable with which one can predict the effect of varying the volume and concentration of the reinforcer and the reinforcement schedule. This is in sharp contrast with traditional accounts of these data. For example, Bonem and Crossman (1988) reviewed the Collier and Myers (1961) data and concluded that "volume and concentration have been reported to interact in an unpredictable manner" (p. 349).

Although none of these four studies reported sucrose consumption, a very similar study—

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Fig. 2. Response rate (R/minute) is shown as a function of unit price for four studies in which rats responded for a sucrose solution that was available under a fixed-interval schedule of reinforcement [unit price = fixed interval ÷ (volume × concentration)]. The data represent group means. The top four graphs show data taken from three experiments by Collier and Myers (1961) separately and as a group. The bottom three graphs show data taken from Guttman (1953, 1954) and Stebbins et al. (1959). The data from Guttman (1954) include responding for a glucose solution. A line of best fit was determined for each data set using a quadratic equation.

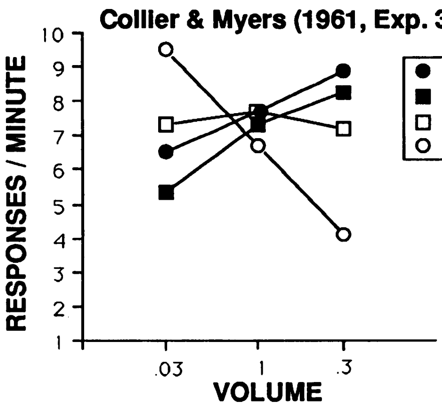

Fig. 3. Response rate (R/minute) is plotted as a function of volume of a sucrose solution. Data are from Collier and Myers (1961, Experiment 3, Figure 3) and represent a mean of five sessions. Symbols indicate different combinations of concentration of reinforcement (percentage sucrose) and duration of fixed-interval schedule (in minutes).

one that did *not* report session response rates—did report sucrose consumption (Collier & Willis, 1961; response rate could not be determined from the consumption data in this study because of the imperfect correlation between rate of responding and rate of reinforcement with interval schedules). As in Experiment 3 by Collier and Myers (1961), this study manipulated FI schedule (1 min and 4 min), sucrose concentration (4, 16, and 64%), and sucrose volume (0.1 and 0.3 mL). Consumption (sucrose) data are plotted as a function of unit price [unit price = FI ÷ (concentration × volume)] in Figure 4.[1] These consumption data demonstrate functional equivalence across different reinforcer-magnitude manipulations in a manner similar to the response-rate data shown in Figure 2. Also, both data sets (3-hr and 23-hr deprived) show a generally linear decrease in consumption, a finding inconsistent with previous research reporting that elasticity increases as unit price increases (e.g., see Allison, 1981; Bickel et al., 1991; Hursh et al., 1988). Overall, these five studies of sucrose-maintained responding show functional equivalence across different reinforcer-magnitude and schedule manipulations, and suggest a bitonic function for response rate.

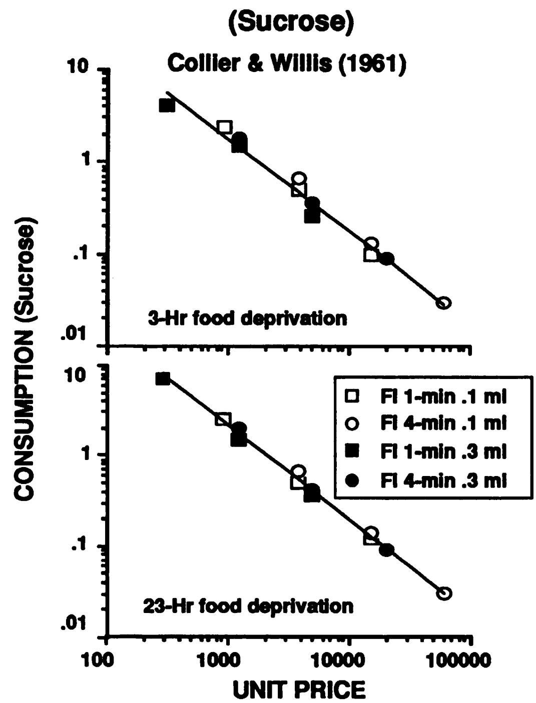

Fig. 4. Consumption of a sucrose solution (milliliters) is shown as a function of unit price for a study (Collier & Willis, 1961) in which rats responded for sucrose that was available under a fixed-interval schedule of reinforcement [unit price = fixed interval ÷ (volume × concentration)]. The data represent group means. The top and bottom graphs show consumption when animals were food deprived for 3 and 23 hr, respectively. A line of best fit is shown for each data set that was derived from a multiple regression equation. See text for further description.

Daily ration. Five additional studies (eight experiments) that examined food-maintained responding using part (open economy) or all (closed economy) of the animals' daily food ration as the reinforcer are examined next. As with the sucrose studies examined above, the most comprehensive of these four studies will be discussed first (Peden & Timberlake, 1984). In this closed-economy study, two experiments were conducted that examined the effects of duration of food presentation (3, 9, or 15 s) on deprived pigeons' response rate and consumption (Experiments 2 and 3; Experiment

[1] A line of best fit was determined for the consumption (C) data using a similar regression equation originally presented by Hursh et al. (1988; Equation 4): $\ln C = \ln L + b(\ln P) - aP$, where a is a measure of the rate of change in slope, b is a measure of the initial slope at the unit price of 1.0, and L is a measure of the intercept at the unit price of 1.0, all of which are derived from the actual unit prices and the consumption levels observed at those unit prices. The regression analyses were conducted with a Macintosh® computer using SuperAnova® software.

Table 1
Synopsis of studies reviewed.

Study	Year	Species	Unit-price factors	Session length	Dose	Force	Route
Sucrose							
Collier and Myers	1961	Sprague-Dawley rats		30 min (open?)		0.26 N	oral
Experiment 1			FI 60, 240 s, concentration		0–64%		
Experiment 2			FI 60 s, volume 0.03, 0.1, 0.3 mL, concentration		4, 32%		
Experiment 3			FI 60, 240 s, volume 0.03, 0.1, 0.3 mL		32, 64%		
Guttman	1953	albino rats	PR 1, concentration	30 min (open?)	4–32%	unreported	oral
Guttman	1954	white rats	PR 1, concentration	1 hr (open?)	2–32%	unreported	oral
Stebbins, Mead, and Martin	1959	albino rats	FI 60 s, concentration	2 hr (open?)	5–50%	unreported	oral
Collier and Willis	1961	Sprague-Dawley rats	FI 60 s, 240 s, concentration	30 min (open?)	4–64%	unreported	oral
Food							
Peden and Timberlake	1984	White Carneau pigeons		3 hr	not applicable	unreported	oral
Experiment 2			FR 10–300, duration of access				
Experiment 3			VI 30, 240 s, duration of access				
Catania	1963	White Carneau pigeons	VI 120 s, duration of access	unreported	not applicable	unreported	oral
Collier, Johnson, Hill, and Kaufman	1986	Sprague-Dawley rats		24 hr	22, 97 mg	0.35 N	oral
Experiment 1			FR 160, CFR 5–120,[a] pellet size				
Experiment 2			FR 8–2,500 CRF 20,[a] pellet size				
Collier, Johnson, and Morgan	1992	Sprague-Dawley rats					oral
Experiment 1 open closed-free closed-restricted			FR 10, 40, pellet size	24 hr (closed)	20, 45, 97 mg	0.35 N	
Experiment 2			FR 10, 40, pellet size	30 min (open)			
Kliner, Lemaire, and Meisch	1986	albino rats		3 hr	45 mg	unreported	oral
Experiment 2			FR 64, 128, CRF 1–16, no. of pellets	(open)			
Experiment 3			FR 128–2,048, CRF 1–512, no. of pellets	(open)			

Table 1 (*Continued*)

Study	Year	Species	Unit-price factors	Session length	Dose	Force	Route
Cocaine							
Goldberg	1973	squirrel monkey	FR 10, FR 30, concentration	100 min	6–100 μg/kg	0.27 N	IV
Goldberg and Kelleher	1976	squirrel monkey	FR 10, 30, concentration	100 min or 10 del	12–200 μg	unreported	IV
Meisch, George, and Lemaire	1990	rhesus monkeys	VR 8, concentration	3 hr	3.1–800 μg	unreported	IV
Downs and Woods	1974	rhesus monkeys	FR 30, concentration	2 hr or 48 inj	1–3 μg/kg	unreported	IV
Spear, Muntaner, Goldberg, and Katz	1991	squirrel monkeys	FR 10, concentration	100 min	3–100 μg	unreported	IV
Wilson, Hitomi, and Schuster	1971	rhesus monkeys	FR 1, concentration	4 hr	25–1,200 μg/kg	0.98 N	IV
d-Amphetamine							
Glick, Hinds, and Carlson	1987	Long-Evans rats	FR 1, concentration	1 hr	40–160 μg/kg	unreported	IV
Pickens and Harris	1968	albino rats	FR 1, concentration	24 hr	250–500 μg/kg	unreported	IV
Wellman, Shelton, and Schenk	1989	Sprague-Dawley rats	FR 1, concentration	3 hr	5–80 μg/inj	unreported	IV
Goldberg	1973	squirrel monkey	FR 10, FR 30, concentration	100 min	6–100 μg/kg	0.27 N	IV
Hammerbeck and Mitchell	1978	rhesus monkeys	FR 10, concentration	8 hr	10–100 μg	unreported	IV
Procaine							
Hammerbeck and Mitchell	1978	rhesus monkeys	FR 10, concentration	8 hr	15–12,000 μg	unreported	IV
Johanson	1980	rhesus monkeys	FR 10, concentration	3 hr	100–3,200 mg	unreported	IV
Codeine							
Downs and Woods	1974	rhesus monkeys	FR 30, concentration	2 hr or 48 inj	1–1,000 μg/kg	unreported	IV
Hoffmeister and Schlichting	1972	rhesus monkeys	FR 10, concentration	3 hr	0.1–500 μg	0.49 N	IV
Morphine							
Harrigan and Downs	1978	rhesus monkeys	FR 1, concentration	15 min every 4 hr	2–250 μg	unreported	IV
Hoffmeister and Schlichting	1972	rhesus monkeys	FR 10, concentration	3 hr	0.01–500 μg	0.49 N	IV
Methohexital							
Spear, Muntaner, Goldberg, and Katz	1991	squirrel monkeys	FR 10, concentration	100 min	25–400 μg	unreported	IV
Winger, Stitzer, and Woods	1975	rhesus monkeys	FR 1, concentration	3 hr	125–2,000 μg/kg	unreported	IV
Pentobarbital							
DeNoble, Svikis, and Meisch	1982	rhesus monkeys	FR 8–16, concentration	3 hr	2,000–4,000 μg/mL	lip contact response	oral
Lemaire and Meisch	1984	rhesus monkeys	FR 16–256, concentration	3 hr	625–4,000 μg/mL	lip contact response	oral
Meisch, Kliner, and Henningfield	1981	rhesus monkeys	FR 16–64, concentration	3 hr	62.5–4,000 μg/mL	lip contact response	oral

[a] CFR = consumption fixed ratio.

1 did not manipulate reinforcer magnitude). Experiment 2 employed an FR schedule, and Experiment 3 employed a variable-interval (VI) schedule.

Specifically, in Experiment 2, Peden and Timberlake (1984) reported response rate (key pecks) and consumption for 1 pigeon (Subject 6707). They plotted the data as a function of price (pecks per gram of food, determined post hoc) on arithmetic coordinates (see their Figure 7). This measure of price is not identical to the unit-price ratio used above; instead of dividing the duration of food presentation into the response requirement (i.e., unit price), they divided the actual consumption (grams) for each condition into the schedule requirement (i.e., pecks per gram eaten). Both price ratios are used below in presenting the data from this experiment.

These data are plotted as a function of both price (pecks per gram; left graphs) and unit price (right graphs) on log coordinates in Figure 5. A comparison of these two cost-benefit ratios indicates that both measures of price show very similar effects for reinforcer magnitude; that is, similar variability exists in the data regardless of the ratio used. The overlapping data points suggest the functional equivalence of the response-requirement and reinforcer-magnitude manipulations: Both the response-rate and consumption data—when plotted as a function of either price or unit price—show a consistent effect across the three magnitude durations such that consumption is a positively decelerating function and response rate is a bitonic function of price. This conclusion, however, contrasts with the authors' conclusion that "it is unclear whether there is one general function or whether there is a separate function for each magnitude of reward" (pp. 407–408). These different interpretations may stem from the fact that Peden and Timberlake (1984) plotted the data on arithmetic coordinates.

In Experiment 3 of Peden and Timberlake (1984), the effects of reinforcer magnitude (duration of food presentation) on consumption and response rate were determined in a closed economy for 3 subjects (Subjects 7239, 8856, and 7535) responding under VI schedules and were plotted in generally the same manner as in Experiment 2 (i.e., grams eaten as a function of pecks per gram). Thus, for this experiment, the unit-price ratio used in this paper (which uses the schedule interval as a cost factor) differs significantly from the price ratio used by Peden and Timberlake (1984) (pecks per gram).

The data from Experiment 3 are shown in Figure 6 on log coordinates as a function of price (top graphs) and unit price (bottom graphs). These data demonstrate functional equivalence of the reinforcer-magnitude and schedule manipulations, regardless of which ratio is used. In fact, visual inspection of the differences between the two ratios suggests that both provide a similar and reasonable account of the variability in the data, thus indicating that either the responses emitted or the interval can be used as cost factors. It is important to note, however, that the data from these two experiments, when plotted on a single set of coordinates as a function of price (i.e., pecks per gram; see Figure 7), show remarkably similar effects of this variable (price), despite the fact that one reinforcement schedule was time based and the other was response based. (Peden & Timberlake, 1984, noted the similarity across these two reinforcement schedules but did not plot the data on a single set of coordinates.) The difficulty in resolving the issue of what is the cost factor across ratio and interval schedules stems in part from the fact that the effects of these schedules are not easily separated because interreinforcement interval (IRI) and responses emitted are typically positively correlated. Overall, because prospective studies have produced discrepant findings in suggesting that both responses emitted (Peden & Timberlake) and time (i.e., schedule interval; Bauman, 1991) are the "best" measures of cost, further research will be necessary to determine the precise role of different cost factors in the definition of unit price.

These data also suggest a generally linear relationship between consumption (and response rate) and unit price. These effects of unit price, however, differ from Peden and Timberlake's (1984) conclusion that the response-rate data in Figure 6 were "unaffected by magnitude of reward" and that the data from the 240-s VI schedule "confirmed Catania's (1963) report that key pecking on simple variable intervals was insensitive to manipulations of magnitude of reward" (p. 412). However, these data, whether plotted as price or unit price, seem inconsistent with this conclusion regarding the effects of reinforcer mag-

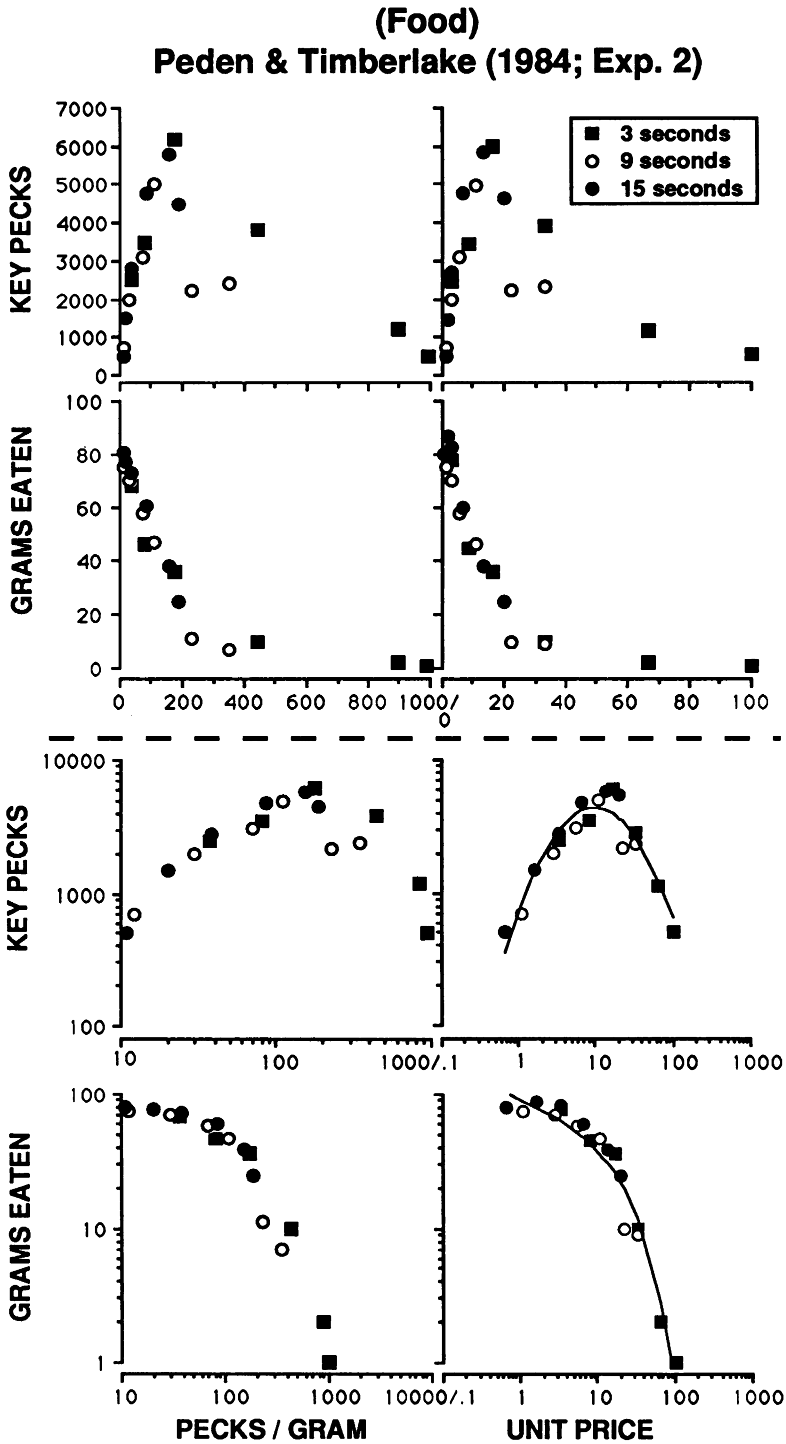

Fig. 5. Key pecks and consumption (grams) are shown for a single pigeon as a function of both price (pecks per gram; left four graphs) and unit price (fixed ratio ÷ food duration; right four graphs) when plotted on arithmetic (top four graphs) and log coordinates (bottom four graphs). Thus, the same data are shown in the top four graphs and the bottom four graphs. Data were taken from Peden and Timberlake (1984, Experiment 2). Symbols represent data from each of the different durations of access to food. A line of best fit (where shown) was determined using a quadratic or a multiple regression equation. See text for further description.

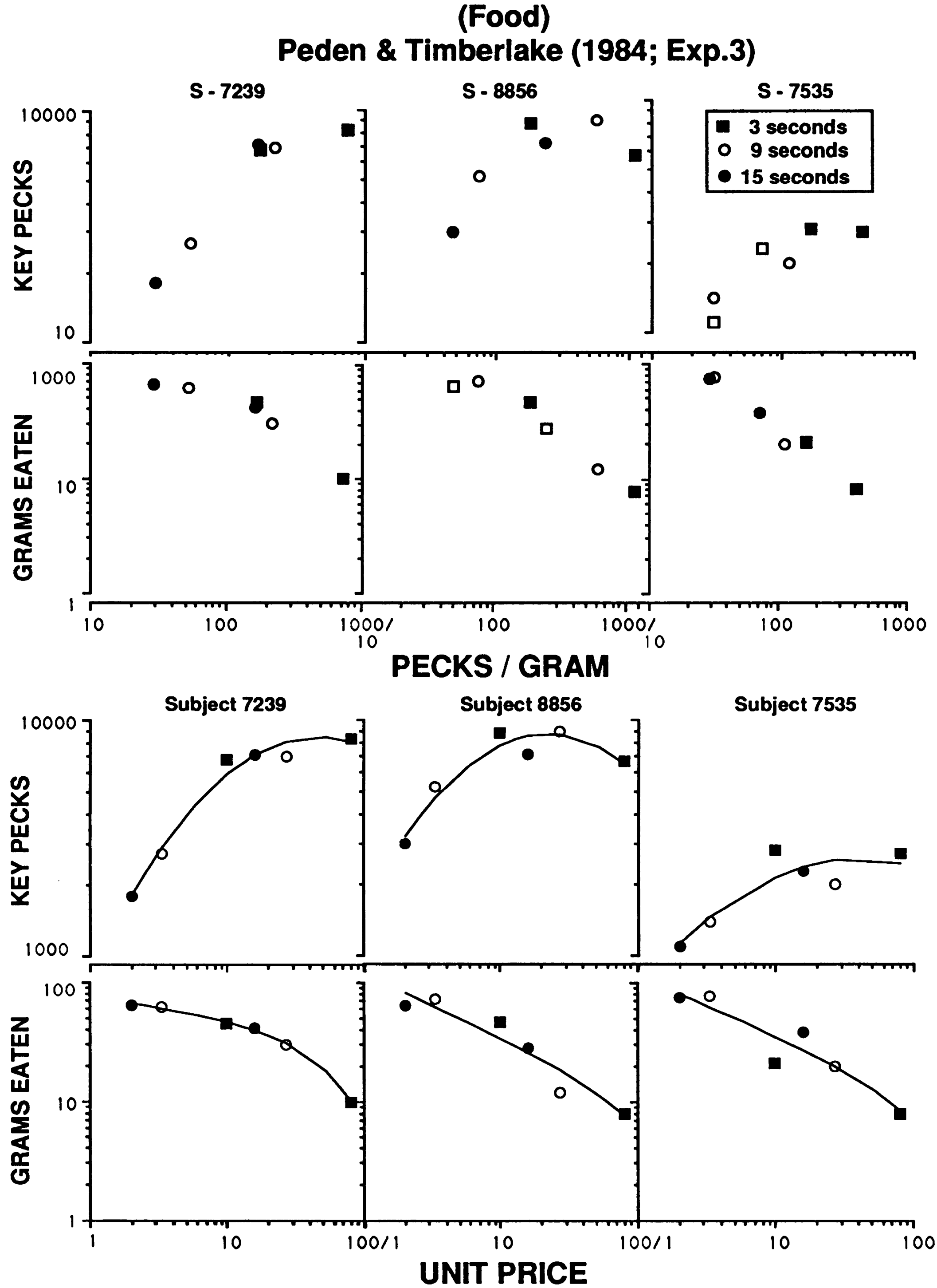

Fig. 6. Key pecks and consumption (grams) are shown for three pigeons as a function of both price (pecks per gram; top six graphs) and unit price (VI duration ÷ food-access duration; lower six graphs) when plotted on log coordinates. Thus, the same data are shown in the top six graphs and the lower six graphs. Data were taken from Peden and Timberlake (1984, Experiment 3). Symbols represent data from each of the different durations of food access. A line of best fit was determined for each data set plotted in terms of unit price using a quadratic or multiple regression equation. See text for further description.

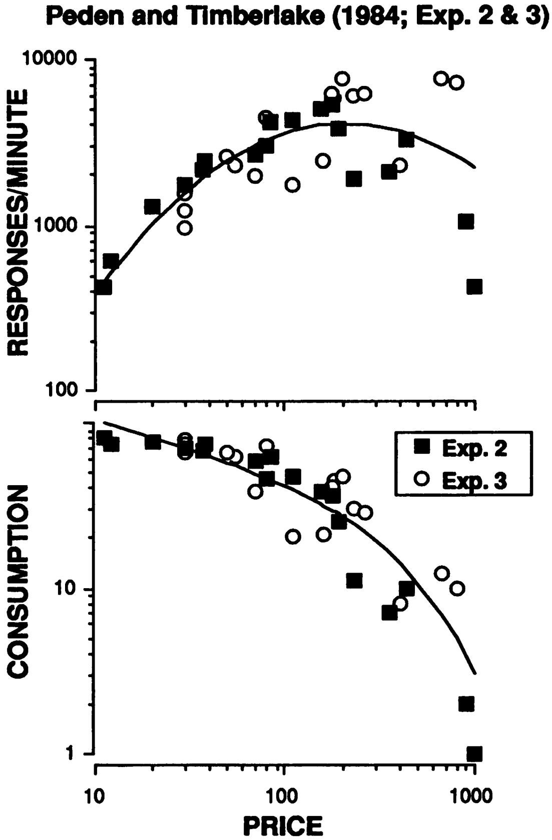

Fig. 7. Key pecks and consumption (grams) are shown for single pigeon from Experiment 2 of Peden and Timberlake (1984) and from the 3 pigeons in Experiment 3 of the same study as a function of price (pecks per gram) when plotted on log coordinates. Symbols represent data from the two experiments. A line of best fit was determined for each data set using a quadratic or a multiple regression equation. See text for further description.

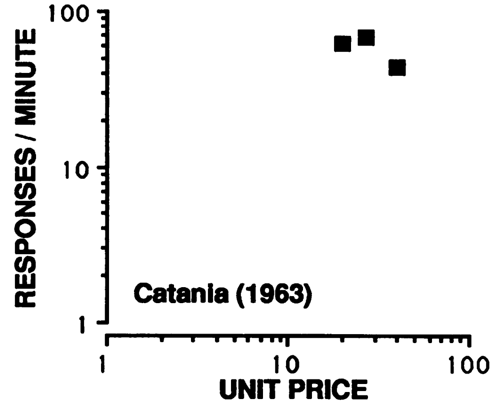

Fig. 8. Response rate (R/minute) is plotted as a function of unit price (VI duration ÷ food-access duration). Data were taken from Catania (1963) and are plotted as a group mean on log coordinates. To allow comparisons with the data plotted in Figure 6, the x-axis values are the same as those used in Figure 6 when the latter data were plotted as a function of unit price.

nitude under VI schedules. An analysis of the "240-s data" (right-most three data points when plotted as a function of unit price; third row, Figure 6) shows that the lack of an effect of reinforcer magnitude under this schedule occurs because the prices fall on the flatter portion of the putative bitonic function. The unit-price function suggests that if the reinforcer magnitudes under this schedule produced prices low or high enough to fall on the ascending or descending portion of the function, the conclusion regarding magnitude manipulations under VI schedules would be different. In fact, this is consistent with the conclusions drawn by Peden and Timberlake regarding the "30-s data" (i.e., those data that fell on the ascending portion of the bitonic function—left-most three data points when plotted as unit price; see Figure 6). We show the data from Catania (1973) in terms of unit price to highlight the possibility that the lack of effect reported in this later study is also due to assessing prices that fall on the relatively flat portion of a bitonic function (see Figure 8; cf. Figure 6). Note that Catania's study does not meet the criteria for inclusion in this analysis because it produced only three data points.

Figure 9 shows data from three studies (six experiments) that examined food-maintained responding in rats while volume of reinforcement was varied in both open and closed economies (Collier, Johnson, Hill, & Kaufman, 1986; Collier et al., 1992; Kliner, Lemaire, & Meisch, 1986). Although each of these studies employed simple FR schedules, the two Collier et al. studies modeled animal foraging and employed additional "procurement" procedures. Also, the Collier et al. (1986, Experiment 1) and Kliner et al. studies (Experiments 2 and 3; Experiment 1 did not manipulate reinforcer magnitude) employed a continuous reinforcement schedule (CRF) to deliver a varied number of food pellets after an initial FR was completed. These differences in procedure within and across studies limit the across-experiment and across-study comparisons that can be drawn because the unit-price factors are not identical.

The different magnitude manipulations in

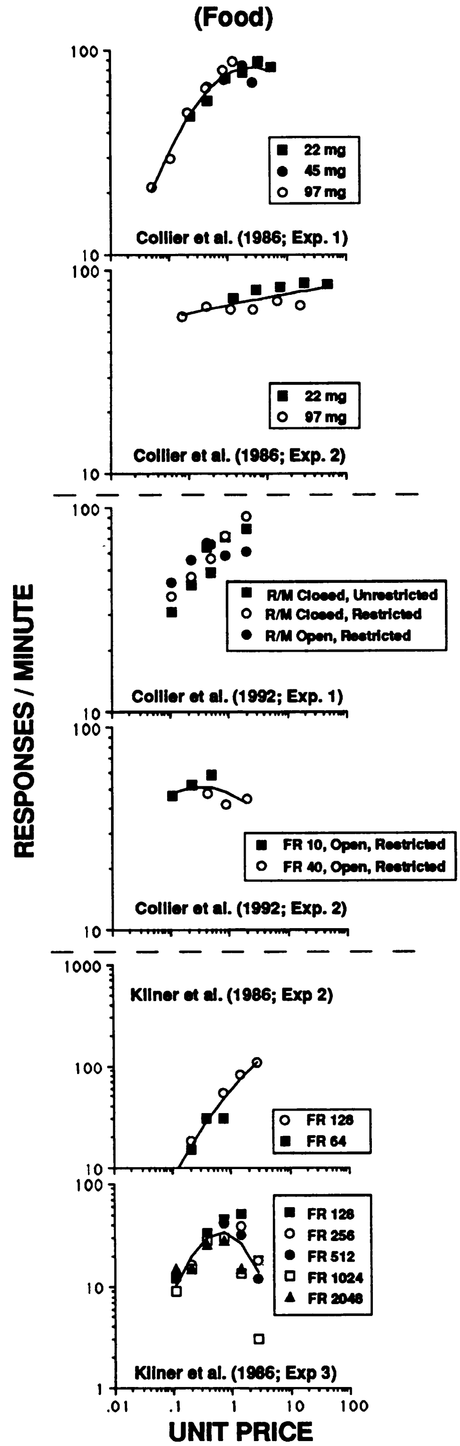

Fig. 9. Response rate (R/minute) is shown as a function of unit price for three studies in which rats responded for food pellets that were available under a fixed-ratio schedule of reinforcement (unit price = fixed ratio ÷ pellet weight). The data represent group means. The top two graphs show data from the two experiments of Collier et al. (1986). Symbols represent data from each of the different pellet-size conditions. The middle two graphs show data from the two experiments of Collier et al. (1992). Symbols represent data from three separate conditions in which food deprivation (restricted or free feeding) and access to postsession food (open or closed) differed. The lower two graphs show data from Kliner et al. (1986, Experiments 2 and 3). Symbols represent data from each of the different fixed-ratio conditions. A line of best fit is shown for each data set that was derived from a quadratic equation.

Collier et al. (1986, Experiments 1 and 2, top two graphs; Figure 9) produced similar effects within each experiment such that the data generally overlap, suggesting functional equivalence between the schedule and reinforcer-magnitude manipulations. Although these data show somewhat different functions, response rate is positively related to unit price in both experiments.

The Collier et al. (1992) study examined the relationship between response rate and reinforcer magnitude in three feeding conditions: a closed economy with unrestricted feeding, a closed economy with restricted feeding to maintain an 85% body weight, and an open economy with restricted within-session feeding and postsession feeding. Thus, data were reported from closed (Experiment 1) and open (Experiments 1 and 2) economies, and the animals responding in the open economy in Experiment 2 did not have the history of a closed economy that the subjects in the open economy in the first experiment did. In Experiment 1, Collier et al. reported that in the closed economy—regardless of the restrictedness of feeding or the subject's body weight—response rate increased as pellet size decreased or when the FR increased. This can be seen in Figure 9 in terms of unit price, in which the two closed-economy functions are very similar and show increases in response rate with increases in unit price (no line of best fit is shown for the data from Experiment 1 because a separate function for each condition is necessary and would clutter the figure). The data from the open economy in Experiment 1, however, suggest a bitonic function. The data from Experiment 2 (open economy, restricted feeding) span a narrow range of unit prices and are thus difficult to interpret, but are not inconsistent with the open-economy data from Experiment

1, which suggest a bitonic function for response rate.

The data from Kliner et al. (1986) also show an increase in response rate as unit price increases (Experiments 2 and 3), followed by an asymptote and decrease in response rate at higher unit prices (Experiment 3). Again, the differences in the procedures of the two experiments may account for the differences between the two data sets. Overall, despite the differences in procedure across the three studies (six experiments) shown in Figure 9, the unit price at which response rate is maximum is generally similar at about 1.0.

Summary. The primary finding in this section is that different reinforcer-magnitude manipulations appear to have, when expressed in unit-price terms, functionally equivalent effects on rates of responding, and that these effects are also functionally equivalent to reinforcement-schedule manipulations. Within, and to a lesser extent, across studies, manipulating the concentration, duration, volume, and schedule of reinforcement appeared to interact as contributors to a single variable (quantified here as unit price) that determines within-session response rates and consumption. The notion that the behavioral effects of reinforcer magnitude are consistent across different magnitude manipulations is supported by these data, the most compelling of which are from Collier and Myers (1961) and Collier and Willis (1961) in which concentration and volume (and FI) were varied, Peden and Timberlake (1984) in which duration and schedule (FR and VI) were varied, and Collier et al. (1986) in which volume and schedule (FR) were varied.

These data, when taken together, also lend further support for the finding in previous unit-price analyses of food- and drug-maintained responding of a positively decelerating curve for consumption and a bitonic function for response rate when examined across a broad range of unit prices (Bickel et al., 1990; Hursh et al., 1988; Lea & Roper, 1977). Even though bitonic functions for response rate are not widely cited in the simple-schedule literature for food-maintained behavior in open economies, the finding of a bitonic function does not appear to be restricted to closed economies. For example, a bitonic function exists for the food-maintained responding in the studies of Kliner et al. (1986, Experiment 2) and Peden and Timberlake (1984), who employed an open economy and a closed economy, respectively. The data from the open-economy conditions in Collier et al. (1992, Experiments 1 and 2) also show a bitonic function. Overall, the data supporting the notion of a bitonic function for responding maintained by food, albeit not overwhelming, certainly indicate the need for future research that examines the effects of reinforcer magnitude across a broader range of magnitudes (or unit prices). Use of a broad range of reinforcer magnitude is, however, more common in the study of drug-maintained responding.

Reinforcer Magnitude and Drug-Maintained Responding

The purpose of reviewing data from studies examining drug reinforcement is to examine the generality of the findings reported above. Historically, the study of reinforcer magnitude has not included drugs as reinforcers, even though hundreds of studies have demonstrated that drugs maintain operant responding (see Young & Herling, 1986). Drug consumption is typically shown as milligrams per milliliter (absolute amount) or micrograms per kilogram (relative to body weight); drug consumption is shown below as absolute amount (micrograms per milliliter) except when only relative amounts were available and subjects' body weights were not reported, thus precluding a determination of absolute amount. Studies that used stimulants as a reinforcer are discussed first, followed by studies that used opioid drugs and barbiturate drugs. As in the previous section, the functional equivalence of reinforcer-magnitude and schedule manipulations will be described for each study first, followed by the shape of the function for consumption and response rate.

Stimulants. Six studies were identified that examined intravenous cocaine-maintained responding in monkeys (rhesus or squirrel monkeys) under an FR schedule of reinforcement (Downs & Woods, 1974; Goldberg, 1973; Goldberg & Kelleher, 1976; Meisch, George, & Lemaire, 1990; Spear, Muntaner, Goldberg, & Katz, 1991; Wilson, Hitomi, & Schuster, 1971). Drug consumption (if reported) and response rates are shown as a function of unit price (FR÷drug dose [μg]) for each study in Figure 10. Note that data from the studies shown in the top five graphs are plotted with

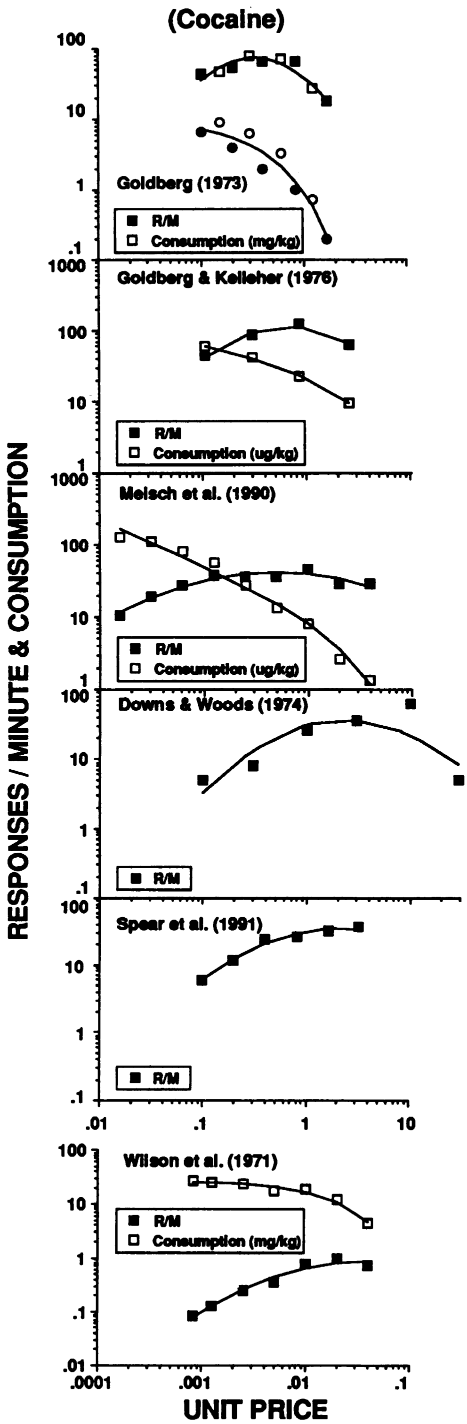

Fig. 10. Consumption of a self-administered drug (cocaine) and response rates by monkeys (R/minute) are plotted as a function of unit price in each of the six graphs (unit price = fixed ratio ÷ drug dose [μg]). Data are group means and are shown on log coordinates. Each graph represents data taken for a different study. Symbols indicate whether the data represent response rates or consumption and whether the response requirement was an FR 10 or FR 30 (solid and open, respectively, in the top graph). Data in the top five graphs are plotted with the same x-axis values, but these values differ from the x-axis values in the bottom graph. A line of best fit is shown for each data set that was derived from a quadratic equation. See text for further description.

the same x- and y-axis values; these values are different from the values on the x and y axes shown for the bottom graph (Wilson et al., 1971).

The data from the one study that manipulated both response requirement and reinforcer magnitude (Goldberg, 1973) show similar response rates (and consumption) at similar unit prices. Data from the four studies that reported cocaine consumption produced similarly shaped functions: Cocaine consumption decreased as unit price increased (i.e., elasticity of demand was similar across studies). Four of the six studies show a bitonic function for response rate (top four graphs, Figure 10; Downs & Woods, 1974; Goldberg, 1973; Goldberg & Kelleher, 1976; Meisch et al., 1990). The shape of this function across these four studies is similar, whereas the two remaining response-rate functions (bottom two graphs; Spear et al., 1991; Wilson et al., 1971) are monotonic. The unit prices representing the maximum response rates vary; the maximum rates for the data from Goldberg (1973), Goldberg and Kelleher (1976), and Meisch et al. (1990) are similar (i.e., unit price < 1.0), as are unit prices for the maximum rates for the data from Downs and Woods (1974) and Spear et al. (1991) (i.e., unit price > 1.0). Differences in the unit price producing the maximum response rate may result, in part, from differences in session lengths across the six studies. The differences, however, are not correlated with species of monkey (i.e., rhesus vs. squirrel). Comparing the response rate and consumption function within studies suggests that the maximum response rates occurred at a unit price at which the slope of the consumption function was approximately -1.0.

Finally, the clear differences between the data from Wilson et al. (1971) and the remaining five studies may be due to an unusually high lever weight used in the former study. The force required to complete a response on the manipulandum in the Wilson et al. study

(0.98 N) was greater than for any other study reporting a force requirement that examined responding by monkeys. Consistent with Wilson et al.'s data, increasing the force requirement without entering it into the unit-price ratio would have the functional effect of shifting the unit-price function to the left (i.e., the maximum response rate would occur at a lower unit price). Because lever weight was unreported in four of these six studies, we could not incorporate lever weight into the unit-price ratio without further limiting the number of comparisons (see Hursh et al., 1988, for such an attempt with FR schedules).

Figure 11 shows data from three studies examining responding maintained by *d*-amphetamine in rats under an FR schedule of reinforcement (Glick, Hinds, & Carlson, 1987; Pickens & Harris, 1968; Wellman, Shelton, & Schenk, 1989). The data from Pickens and Harris (1968) show functional equivalence between the FR schedule and dose manipulations. These data, however, do not show a bitonic function for response rate; instead, response rate increased in a monotonic fashion as unit price increased, with the slope of this increase consistent across studies. Although a bitonic function exists for the Glick et al. study, this is due to a single data point.

Responding maintained by *d*-amphetamine is shown in Figure 12 for monkeys (rhesus and squirrel) responding under an FR schedule (Goldberg, 1973; Hammerbeck & Mitchell, 1978). The data from Hammerbeck and Mitchell, like the *d*-amphetamine data from Pickens and Harris (1968) shown in Figure 11, show functional equivalence between the FR schedule and the magnitude manipulation. The data from both studies in Figure 12 generally show a linear increase in response rates (and a linear decrease in consumption) with increases in unit price, although the single data point at the highest unit price in Goldberg's study suggests a bitonic function for the response-rate data and a positively decelerating function for consumption. Overall, these data on *d*-amphetamine self-administration show functions for response rate and consumption that are more often monotonic than are functions found in the unit-price studies described above.

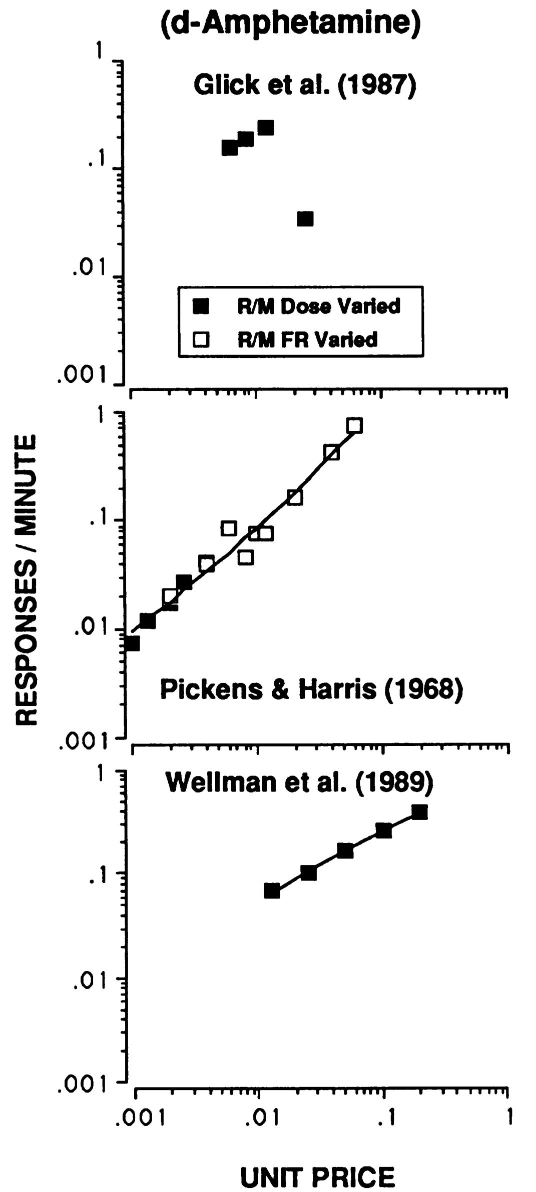

Fig. 11. Response rates (R/minute) by rats for a self-administered drug (*d*-amphetamine) are plotted as a function of unit price in each of the three graphs (unit price = fixed ratio ÷ drug dose [μg]). Data are group means and are shown on log coordinates. Symbols indicate whether changes in unit price are due to variations in fixed-ratio schedule or dose. Lines of best fit were derived from a quadratic equation. See text for further description.

Data from two studies that examined procaine-maintained responding in rhesus monkeys under an FR schedule of reinforcement are shown in Figure 13 (procaine is a local anesthetic) (Hammerbeck & Mitchell, 1978; Johanson, 1980). Unlike the *d*-amphetamine data from Hammerbeck and Mitchell shown in Figure 12, their procaine data do not show

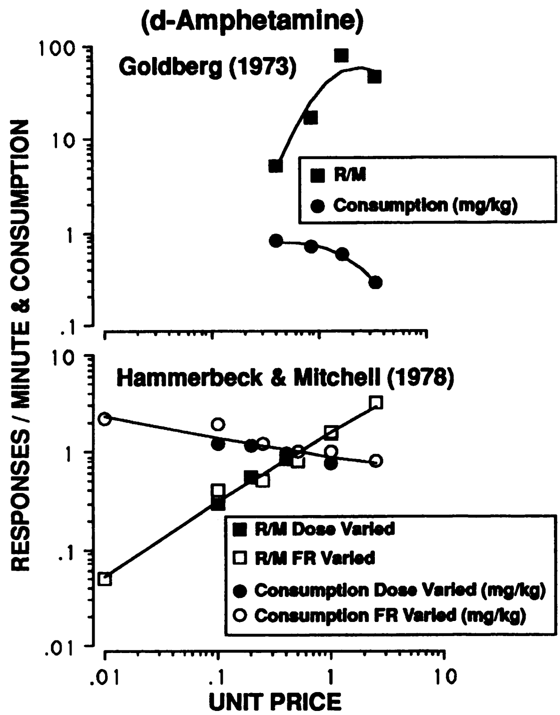

Fig. 12. Consumption of a self-administered drug (*d*-amphetamine; mg/kg) and response rates by monkeys (R/minute) are plotted as a function of unit price in the two graphs (unit price = fixed ratio ÷ drug dose [μg]). Data are group means and are shown on log coordinates. Symbols indicate whether the data represent response rates or consumption and whether changes in unit price are due to variations in fixed-ratio schedule or dose. Lines of best fit are derived from either a quadratic or multiple regression equation. See text for further description.

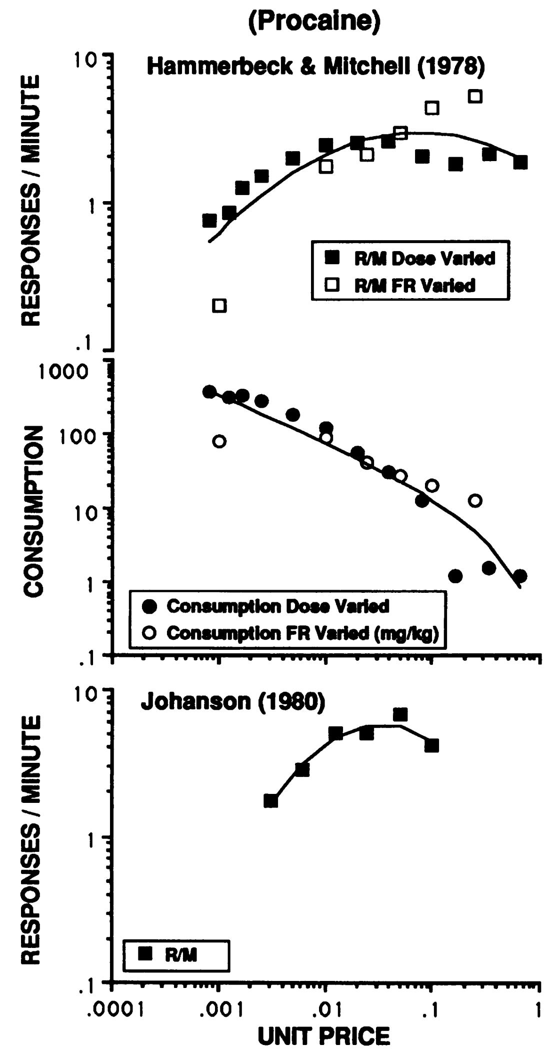

Fig. 13. Consumption of a self-administered drug (procaine; mg/kg) and response rates for monkeys (R/minute) are plotted as a function of unit price (unit price = fixed ratio ÷ drug dose [μg]). Data are group means and are shown on log coordinates. Each graph represents data from a different study. Symbols indicate whether the data represent response rate or consumption and whether changes in unit price are due to variations in fixed-ratio schedule or dose. Data in the top and bottom graphs are response rates, and the middle graph shows consumption from the Hammerbeck and Mitchell (1978) study. A line of best fit is shown for each data set that was derived using a quadratic or a multiple regression equation. See text for further description.

functional equivalence across the dose and schedule manipulation, especially at the higher unit prices. Instead, the function for the dose manipulations suggests a bitonic function for response rate, whereas a monotonic function is suggested for the FR manipulations. Lower values for the dose manipulations at the higher unit prices indicates that response rate and consumption were lower at the lowest doses. This finding appears to be consistent with the previous finding that very low doses may not produce the functional equivalence seen at all higher doses (see Bickel et al., 1990, 1991). Finally, the response-rate function in Johanson's study is generally similar to the response-rate function found by Hammerbeck and Mitchell, and has a similar unit price at which response rate is maximum.

Opioids. Figure 14 shows data representing codeine-maintained responding in rhesus monkeys under an FR schedule of reinforcement for two studies (Downs & Woods, 1974; Hoffmeister & Schlichting, 1972). For both studies, unit price is a function of dose at a

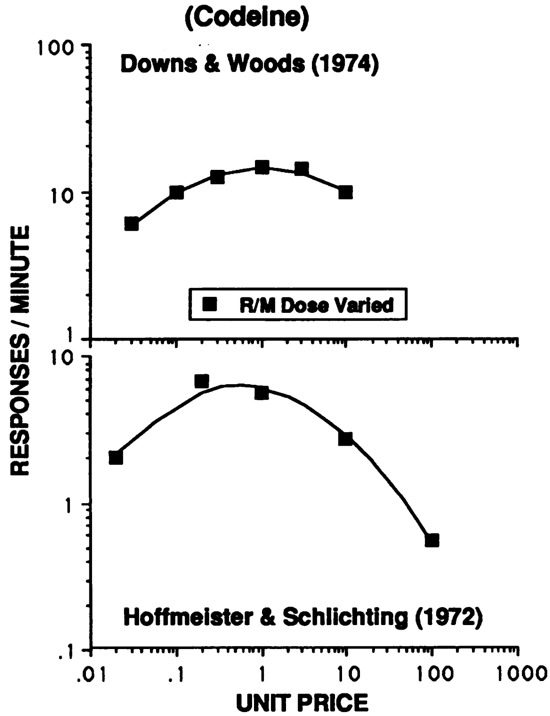

Fig. 14. Response rates (R/minute) by monkeys for a self-administered drug (codeine) are plotted as a function of unit price in each graph (unit price = fixed ratio ÷ drug dose [μg]). Data are group means and are shown on log coordinates. Lines of best fit were derived from a quadratic equation.

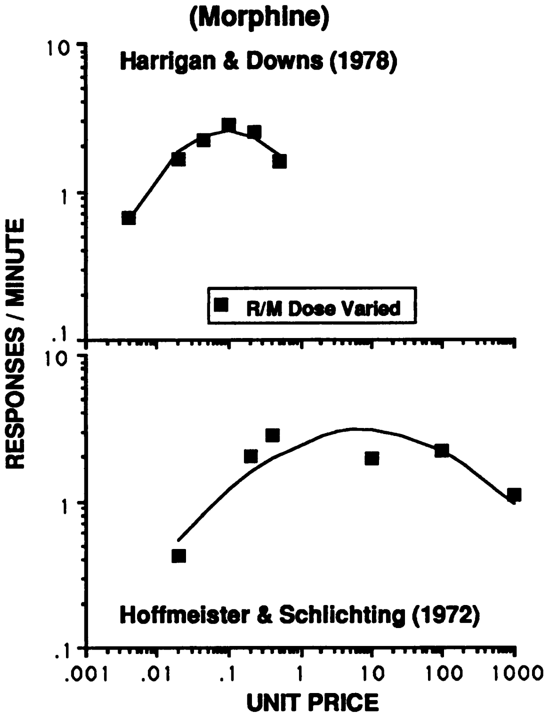

Fig. 15. Response rates (R/minute) by monkeys for a self-administered drug (morphine) are plotted as a function of unit price in each graph (unit price = fixed ratio ÷ drug dose [μg]). Data are group means and are shown on log coordinates. Lines of best fit were derived from a quadratic equation.

constant FR, and the unit prices are very similar, except that Hoffmeister and Schlichting's study examined one significantly lower dose (0.1 μg codeine, unit price = 100 [100 = FR 10 ÷ 0.1]). The response-rate functions for both studies are very similar and show a bitonic relationship for response rate and unit price.

Hoffmeister and Schlichting (1972) also reported morphine-maintained responding under an FR schedule with rhesus monkeys; data from a similar study are also shown in Figure 15 (Harrigan & Downs, 1978). Although the shape of the functions (i.e., bitonic) and the absolute rates of responding are similar across these two studies, the unit price at which response rate is maximum differs.

Barbiturates. Data from two studies examining methohexital-maintained responding in monkeys (squirrel and rhesus, respectively) under an FR schedule of reinforcement are shown in Figure 16 (Spear et al., 1991; Winger, Stitzer, & Woods, 1975). Spear et al.'s data suggest a bitonic function for response rate, whereas the data from Winger et al. show a monotonic function across the unit prices, all of which are lower than in the Spear et al. study. Moreover, the slope of the two ascending functions differs, with the data from Spear et al. showing a greater slope. The source of these differences is unclear and may be partly due to the different unit price.

Three studies were examined in which responding was maintained by another barbiturate, pentobarbital, in rhesus monkeys under an FR schedule of reinforcement (DeNoble, Svikis, & Meisch, 1982; Lemaire & Meisch, 1984; Meisch, Kliner, & Henningfield, 1981) (see Figure 17). Data from these three studies were also reanalyzed in behavioral-economic terms by Bickel et al. (1990). The data from both DeNoble et al. and Lemaire and Meisch show that response rates (and consumption) are similar at similar unit prices, thus suggesting functional equivalence across the

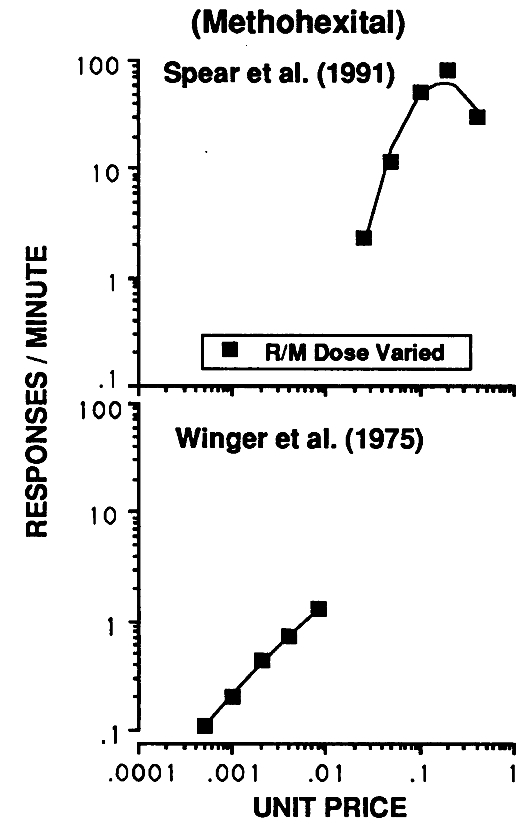

Fig. 16. Response rates (R/minute) by monkeys for a self-administered drug (methohexital) are plotted as a function of unit price in each graph (unit price = fixed ratio ÷ drug dose [μg]). Data are group means and are shown on log coordinates. Lines of best fit were derived from a quadratic equation.

schedule and dose manipulations. Data from two of these three studies produce very similarly shaped functions for response rate and consumption (Lemaire & Meisch, 1984; Meisch et al., 1981); the unit prices representing the maximum response rate for these two studies are approximately 0.25 and 0.35, respectively. Both of these data sets suggest a positively decelerating function for consumption and a bitonic function for response rate. The data from DeNoble et al. are not inconsistent with the results from the other two studies, but show only ascending and descending functions for response rate and consumption, respectively.

Summary. Although these drug self-administration data do not provide an assessment of the functional equivalence of different reinforcer-magnitude manipulations, they are con-

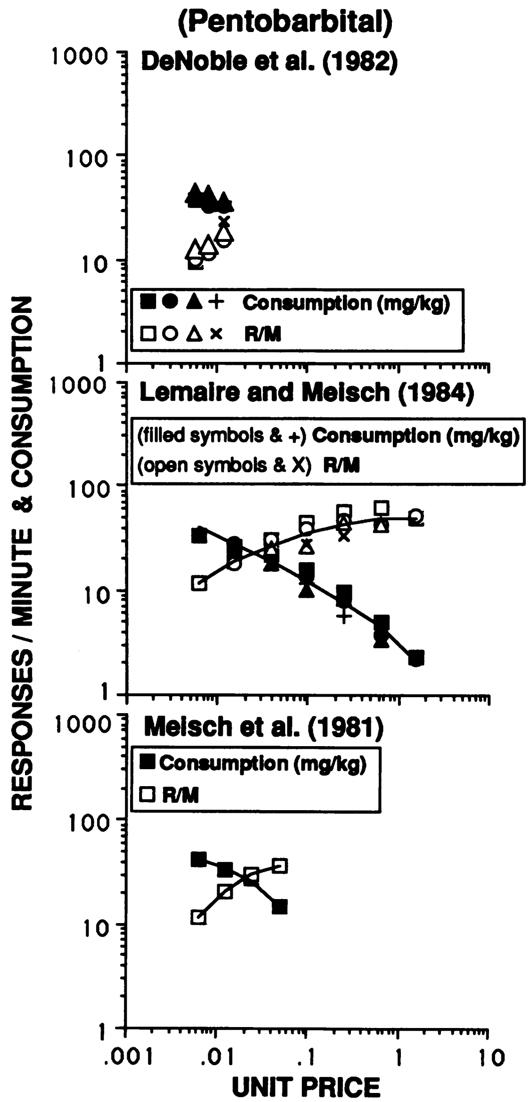

Fig. 17. Consumption of a self-administered drug (pentobarbital; mg/kg) and response rates by monkeys (R/minute) are plotted as a function of unit price (unit price = fixed ratio ÷ drug dose [μg]). Data are group means and are shown on log coordinates. Symbols indicate whether the data represent response rate or consumption and also indicate the different fixed-ratio values (box, circle, triangle, and +/x = FR 4, 8, 16, and 32, respectively, for DeNoble et al., 1982, and FR 16, 32, 64, and 128, respectively, for Lemaire & Meisch, 1984). Lines of best fit were derived using a quadratic equation. A line of best fit is not shown for the data from DeNoble et al. because it could not be discriminated from the data points. See text for further description.

sistent with the data from studies of food reinforcement in generally showing functional equivalence between reinforcer-magnitude and reinforcement-schedule manipulations. In fact, all six drug self-administration experiments that replicated unit price with different values for reinforcer magnitude and reinforcement schedule generally showed equal response rates (or consumption) at equal unit prices (the clearest exception being the procaine self-administration data of Hammerbeck & Mitchell, 1978). This possibility of functional equivalence is consistent with the findings of Bickel et al. (1990), who reanalyzed the data from 10 drug self-administration studies in terms of unit price. Finally, a positively decelerating consumption function and a bitonic function for response rate were common across studies employing the same reinforcer, schedule, and species. This was true for cocaine, procaine, codeine, morphine, and pentobarbital.

IMPLICATIONS OF THE BEHAVIORAL ECONOMICS INTERPRETATION

This paper addresses two basic questions: What are the effects of reinforcer magnitude on response rate (and consumption)? Are these effects consistent across different magnitude manipulations (i.e., concentration, duration, and volume)? These questions were addressed by applying the behavioral-economic concept of unit price to schedule-controlled responding because it allows an integration of different reinforcer-magnitude and schedule manipulations into a single variable. In the remainder of this paper, we discuss the implications of this analysis in terms of these two questions, but defer to future prospective studies for more fine-grained analyses. The latter question is discussed first.

Functional Equivalence Across Different Reinforcer-Magnitude Manipulations

Based on previous unit-price studies and the present findings, we suggest that different reinforcer-magnitude manipulations interact with the schedule of reinforcement to produce quantitatively and qualitatively similar effects. Thus, demonstrating equivalence across multiple reinforcer-magnitude manipulations requires that these manipulations be examined and interpreted in concert with schedule manipulations. In the present analysis, 17 of the 21 experiments that examined similar or equal unit prices with different cost and benefit factors showed functional equivalence across different reinforcer-magnitude and schedule manipulations. The two most compelling data sets supporting this notion came from Hursh et al. (1988; Figure 1 above) in which the FR schedule, probability of reinforcer delivery, volume, and response "force" were varied, and from Collier and Myers (1961; Figure 2 above) in which the FI schedule, concentration, and volume were varied (see also Collier & Willis, 1961). Both of these studies demonstrated that different magnitude (and schedule) manipulations interact as a single variable to determine response rate. Functional equivalence was also shown for response rate in the present analysis across concentration, volume, and an FI schedule of reinforcement (Collier & Myers, 1961), between reinforcement duration and an FR schedule of reinforcement (Peden & Timberlake, 1984, Experiment 2), between reinforcement duration and a VI schedule of reinforcement (Peden & Timberlake, 1984), between reinforcement volume and an FR schedule of reinforcement (e.g., Collier et al., 1986; Meisch et al., 1981), and between reinforcement concentration and an FR schedule of reinforcement (e.g., Goldberg, 1973).

These findings suggest that using the unit-price metric for integrating different reinforcer-magnitude manipulations with reinforcement-schedule manipulations results in uniformity of the effects of these manipulations on response rate and consumption. Our conclusion that different reinforcer-magnitude manipulations have uniform effects, however, contrasts with other reviews of this literature (e.g., Bonem & Crossman, 1988; Collier et al., 1992). For example, Collier et al. suggested that concentration may differ from other reinforcer-magnitude manipulations because—unlike other magnitude manipulations—as concentration increases, qualitative changes may occur in the taste of the reinforcer (i.e., qualitative changes in the reinforcer produce quantitative changes in response rate). The reanalyzed data from Collier and Myers (1961) and Collier and Willis (1961), however, demonstrate that such an interpretation is unnecessary. These data indicate that multiple reinforcer-magnitude manipulations and schedule manipulations can be converted into a single function, relating unit price to response rate and consumption.

Functional equivalence across magnitude and schedule manipulations may have important implications for how we examine and interpret the effects of both of these variables. First and foremost, equivalence suggests that response rate is not a function of reinforcer magnitude alone, independent of schedule size or duration. Rather, the unit-price concept stresses that response rate is a function of the interaction of these cost and benefit factors, and that a single process appears to underlie the effects of both different magnitude manipulations and different schedule manipulations. Methodologically, this implication suggests that a more comprehensive account of the interactions among schedule, magnitude, and economic context is needed. Prospective analyses, such as those of Collier et al. (1992) and Hursh et al. (1988), can elucidate the limits or boundaries of this functional equivalence. One limit already suggested in unit-price analyses of drug self-administration is that very low doses may not produce the functional equivalence seen at higher doses (see Bickel et al., 1990, 1991).

In terms of behavioral theory, functional equivalence suggests that reinforcer-magnitude manipulations should be considered as interchangeable with response-requirement manipulations. This notion stands in contrast with the traditional distinction between the two manipulations in the experimental analysis of behavior and the distinction between dose as a pharmacological manipulation and reinforcement schedule as a behavioral manipulation found in behavioral pharmacology. Consequently, because of this interaction, the effects of any reinforcer-magnitude manipulation will be dependent upon the parameters of the reinforcement schedule, and vice versa. This interaction can be highlighted when applied, for example, to the notion of "ratio strain" (i.e., decreases in response rate at high response requirements). Equivalence suggests that ratio strain is not a function of the ratio requirement per se but rather unit price. Say, for example, that the unit price representing the maximum response rate in a study is 100 responses per milligram (r/mg), and response rate decreased at all higher unit prices. Comparing two unit-price ratios, FR 400 ÷ 4 mg (unit price = 100 r/mg) versus FR 200 ÷ 1 mg (unit price = 200 r/mg), the latter, according to the present results, would produce strain even though the former has a greater response requirement (for further discussion of this point, see Peden & Timberlake, 1984). These implications of functional equivalence are important, given that a rationale is rarely provided to explain why the parameters of the reinforcement schedule are chosen when investigating the effects of reinforcer magnitude.

Effects of Reinforcer Magnitude on Response Rate

If different reinforcer-magnitude and schedule manipulations have functionally equivalent effects on response rate (and consumption), the question remains as to what these effects are. The persistence of this question stems partly from the fact that although magnitude manipulations may have equivalent effects (as shown above), different data sets do not necessarily show the same effect (e.g., a bitonic function). As noted in the introduction, different reviews of this literature have interpreted effects of reinforcer-magnitude manipulations as being discrepant, such that reinforcer magnitude is reported to increase, decrease, or have no effect on response rate. As early as 1966, for example, Morse noted that "the lack of correlation with rate has led to a neglect of magnitude of reinforcement as a factor in schedule-controlled responding, and has fostered the erroneous tendency to regard reinforcement as a constant effect with magnitudes below some threshold value not being reinforcers, and all magnitudes above that value being equally effective reinforcers" (p. 81).

Our analyses suggest either a negatively accelerating, increasing, or bitonic function for response rate and a positively decelerating function for consumption as unit price increases. The possibility of a bitonic function for response rate is not widely cited in the literature on simple schedules for food-maintained behavior in open economies (Bonem & Crossman, 1988). Instead, an increasing monotonic function between response rate and reinforcer magnitude is more commonly cited (see Williams, 1988). The same monotonic function has been assumed for drug-maintained responding (Griffiths, Bigelow, & Henningfield, 1980) such that decreases in response rate at high doses (i.e., low unit prices) are often interpreted as being due to the direct behavioral effects of the drug reinforcer (i.e., drug intoxication).

One implication of a nonmonotonic relationship between response rate and unit price is that it may account for the discrepant findings previously reported. Many of the studies examining the effects of reinforcer magnitude appear to have assumed a monotonic relationship between response rate and reinforcer magnitude, as suggested by the narrow range of reinforcer-magnitude manipulations examined. That is, a narrow range of reinforcement-schedule or reinforcer-magnitude manipulations (i.e., unit prices) will demonstrate an apparently monotonic function, whether it be ascending, flat, or descending, even when a broader range of unit prices would have produced a bitonic function. Thus, failure to assess a broad range of manipulations is more likely to lead to the false conclusion that a linear or monotonic relationship exists between an independent and dependent variable. Note that this is less apparent in the present study because many experiments were excluded by our selection criterion (i.e., they did not produce at least four unit prices). Overall, instead of there being functional differences across different magnitude manipulations, a simpler explanation may be that different studies have examined different portions of a bitonic function. Additional research examining a broad range of unit prices should clarify the issue.

A second implication of a nonmonotonic function for response rate is that conclusions regarding how efficacious a consequent stimulus is can be influenced by what range of unit prices is examined, and may not be due to actual differences in efficacy or "value" of the reinforcer. When a narrow range of unit prices is assessed and the range differs across studies, one reinforcer may be examined at unit prices that produce the ascending limb of the response-rate function (i.e., relatively lower unit prices), whereas another reinforcer may be examined at the flatter portion of the function (i.e., relatively higher unit prices). Although the analyses performed here are only preliminary, they do suggest a need for prospective studies that control for what portion of the response-rate curve (and consumption curve) is examined.

A third implication of a bitonic function for response rate when food is the reinforcer (and a positively decelerating function for consumption) is that behavioral regulation occurs at a molar level that is a function of the prevailing rate of reinforcement, the molar contingencies for long-term food availability, and within-session satiation (see Allison, 1981; Timberlake, 1984; Williams, 1988). This possibility is suggested by the finding that as unit price increases at relatively low unit prices, response rate increases in a manner that produces relatively constant levels of consumption. In other words, as unit price decreases, there is a also a decrease in the rate at which consumption increases. The consumption data reviewed above, regardless of whether interval (e.g., Peden & Timberlake, 1984, Experiment 3) or ratio (e.g., Peden & Timberlake, 1984, Experiment 2) schedules were employed, are generally consistent with this notion of a "leveling of consumption" at low unit prices. In most studies reviewed above, however, it appears that unit prices were not low enough to produce the flat portion of the consumption curve. The possibility that subjects may regulate their food or drug intake is also supported by response patterns in drug self-administration, where individuals self-administer at regular intervals that maintain a constant intake (see Griffiths et al., 1980). Finally, this notion of regulation is consistent with other theories of regulation. For example, Allison's conservation model predicts that, at low unit prices, rate decreases and consumption stays constant such that the organism's energy is conserved for other important activities (see Allison, 1981, 1983, for the mathematical conservation models; see also Collier et al., 1986, 1992; Rachlin & Burkhard, 1978).

The notion of a common mechanism underlying the relationship between unit price, response rate, and consumption (e.g., behavioral regulation) is also supported by evidence indicating the same molar relationship between unit price and response rate (and consumption), regardless of what type of consummatory stimuli serve as reinforcers. The present analysis, along with previous unit-price analyses, provide some preliminary evidence of the same demand function for the consumption of food pellets, sucrose, or glucose, and for opiates, stimulants, and barbiturates. Also, Allison (1981) cites similar data across humans, monkeys, rats, and fish, and for food, heat, safety, and drugs (see also Bickel et al., in press).

In emphasizing similarities across studies and manipulations, we are not suggesting that differences in different independent (and dependent) variables are unimportant. It is likely that these variables account for many of the differences that exist in these data, such as the slope of the consumption function (i.e., elasticity) and the number of log units required to produce the complete function. Nor does emphasizing similarities across studies and manipulations suggest that the specific shape of this function for response rate is similar for all schedules of reinforcement, reinforcers, or economic contexts. For example, if higher overall response rates are produced with VR schedules (e.g., VR 100) than with FR schedules (e.g., FR 100), then response rate (and consumption) will not be the same at the same unit price (e.g., FR 100 ÷ 2 mg vs. VR 100 ÷ 2 mg). The comparison between the FR and VI schedules in the data from Peden and Timberlake (1984) using the price ratio (i.e., pecks per gram), however, suggests that similar functions can be obtained across different types of simple schedules using responses per unit reinforcer as a cost factor.

Focusing on more molar variables also should not imply a view that molecular variables are unimportant (e.g., pattern of responding, preratio pause, interresponse times [IRTs]). Molecular dependent variables (e.g., IRT distributions) have been shown to vary considerably across different independent variables (Ferster & Skinner, 1957; Young & Herling, 1986). Response rate, for example, may be a product of the effects of unit price on both molar (e.g., overall rates of reinforcement) and molecular (e.g., differential reinforcement of IRTs) variables (see Morse, 1966).

CONCLUSION

The unit-price analysis provided here suggests that different reinforcer-magnitude manipulations may produce the same-shaped function for response rate (and consumption), if these functions are construed as an interaction between reinforcer magnitude and the reinforcement schedule. Thus the behavioral-economic concept of unit price provides a simple metric of effects of reinforcer magnitude. The unit-price concept provides a single factor that can incorporate the effects of several independent variables across two important dependent measures (i.e., response rate and consumption).

Despite the apparent merits of the behavioral-economic approach, the view requires additional prospective analyses (such as those outlined above) in order to address several important questions that remain. First, are decreases in response rate with decreases in unit price due to within-session satiation or other variables? Second, how do the effects of unit price interact with food deprivation and post-session feeding? Comparisons across a broad range of unit prices and different economic conditions are necessary to address this question. Third, what is the relevant cost factor in the unit-price ratio—time or "effort" (or both)—and does this depend on other parameters of the experimental setting (e.g., session length)? Answers to these questions have important implications for applying the unit-price concept to clinical issues. Fourth, do differences exist across different reinforcers when examined across a broad range of unit prices? Finally, what are the theoretical implications of the answers to these questions—and the possibility of a bitonic response-rate function—for behavioral theory? These questions are fundamental to solving the paradoxes of reinforcer magnitude, and researching these questions can be facilitated by a behavioral-economic approach.

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